Master Thesis

Voluntary Carbon Markets analysis with planetary boundaries perspective

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Abstract: Voluntary carbon markets (VCMs) have been increasingly recognized as a flexible mechanism for mitigating climate change by allowing entities to offset their emissions beyond regulatory requirements. However, the effectiveness and environmental sustainability of these markets are contingent on their alignment with the planetary boundaries framework, which seeks to define a safe operating space for humanity by identifying and respecting critical Earth system limits. This paper proposes a qualitative assessment methodology for VCMs within the framework of planetary boundaries, drawing on existing methodologies and adapting them for this specific market. The study explores how VCMs can be structured to operate within the safe operating space defined by planetary boundaries, assessing their potential to align with broader environmental sustainability goals beyond just carbon emissions reduction. The paper emphasizes the need for a holistic approach to carbon markets, ensuring that they contribute positively to global environmental sustainability by preserving critical Earth system processes while achieving their primary objective of carbon mitigation.

Keywords: Voluntary Carbon Market, planetary boundaries, climate change, non-additionality, transgression.

1. Introduction

Since the first seven planetary boundaries were assessed in 2009 by Rockstrom [1], they have provided a critical framework for understanding the limits within which humanity can safely operate without causing catastrophic environmental changes. Planetary boundaries define the safe thresholds for key Earth system processes, transgressing these boundaries increases the risk of destabilizing the Earth system, leading to irreversible environmental damage. They have been revised many times, progressively updating how humanity is trespassing on them, from three out of seven in 2015 (climate change, biosphere integrity and nitrogen biogeochemical flow [1]), to six out of nine in 2023 [2] (CO2 concentration, radiative forcing, novel entities [3], phosphorus [4] and nitrogen biogeochemical flows, green water[5], freshwater use, land system change, and functional and genetic biosphere integrity) as methods of analysis have developed.

Various mitigation mechanisms, such as carbon markets, energy efficiency improvements, and incentives for energy savings, have been developed to address the growing environmental challenges. While these mechanisms, including voluntary carbon markets (VCMs), play a crucial role in reducing greenhouse gas emissions, they often focus narrowly on specific goals, like carbon reduction, without considering the broader environmental impacts. The proposed methodology in this paper seeks to integrate the planetary boundaries framework into the evaluation of VCMs. By aligning VCM projects with these boundaries, the methodology ensures that carbon offset efforts do not inadvertently contribute to the degradation of other critical Earth system processes.

Carbon Voluntary Markets respond specifically to the Climate Change CO_2 concentration boundary, having an indirect effect (positive and negative) on the rest of the planetary boundaries, a carbon credit corresponds to the emission of a metric ton of CO2 or the GHG equivalent [6]. The existence of these markets responds to the observed necessity of reducing CO_2 emissions and the difficulty of standardizing and measuring more complete metrics, VCMs have gained increasing attention as a flexible mechanism for mitigating climate change by allowing entities to offset their emissions beyond regulatory requirements. However, the effectiveness and environmental sustainability of these markets are contingent on their alignment with the planetary boundaries framework, which seeks to define a safe operating space for humanity by identifying and respecting critical Earth system limits. In this paper, a more holistic metric is going to be proposed, that reflects not only the effect on one planetary boundary but on all of them. This "Planet Voluntary Market" will incentivize not only the reduction of a number such as CO2 emissions but also the analysis and improvement of earth systems.

The primary objective of this paper is to propose a qualitative assessment for voluntary carbon markets (VCMs) within the framework of planetary boundaries, drawing on the methodology proposed by Engström et al. (2020) [7] and adapting it for this specific market. The focus is on exploring how VCMs can be structured to operate within the safe operating space defined by planetary boundaries, which encompass critical environmental limits necessary for sustaining human activities on Earth. This paper will examine the principles of VCMs, assessing their potential to align with broader environmental sustainability goals beyond just carbon emissions reduction. The study will discuss whether current VCM frameworks adequately address the interconnectedness of Earth system processes and whether modifications are needed to prevent the transgression of other planetary boundaries, such as those related to land use and biogeochemical flows.

Additionally, the paper will explore the theoretical and practical challenges of integrating planetary boundaries into VCMs, proposing a step-by-step guide to adapt the current market to one that considers every boundary. The aim is to develop qualitative guidelines that ensure VCMs contribute positively to global environmental sustainability by preserving critical Earth system processes while achieving their primary objective of carbon mitigation. Through this analysis, the paper seeks to provide a comprehensive understanding of how VCMs can be designed and governed to support long-term environmental integrity within the planetary boundaries framework.

2. State of the Art

This paper will be strongly based on the analysis of the effects of the carbon tax price made by Engström et al. [7]. Where they explore the intersection of carbon pricing mechanisms with the planetary boundaries framework, emphasizing the potential for carbon pricing to mitigate multiple environmental pressures simultaneously. The study underscores the importance of considering planetary boundaries in the design and implementation of carbon markets, as policies that solely focus on reducing carbon emissions might inadvertently exacerbate other planetary pressures, such as land-use change or biogeochemical flows. Traditional carbon markets are government-regulated and operate under a cap-and-trade system, where companies are required by law to limit their emissions. Entities can buy or sell carbon credits to stay within their emission limits, with penalties for non-compliance. In contrast, VCMs allow companies and individuals to offset their carbon emissions on a voluntary basis, beyond what is legally required. VCMs offer flexibility and are driven by corporate social responsibility, enabling participants to invest in projects that reduce or remove emissions, such as reforestation or renewable energy initiatives. This distinction underscores the different motivations and regulatory frameworks behind traditional carbon markets and VCMs, with the latter offering a more flexible and voluntary approach to contributing to climate action. This study is directly relevant to the current paper as it provides a foundational framework for integrating planetary boundaries into carbon pricing strategies, a critical component of VCMs. The methodology proposed by Engström et al. [7] offers a blueprint for ensuring that carbon markets do not only address climate change but also remain within the safe operating space defined by other environmental thresholds.

Other studies already show how it is possible to create a variable carbon tax, Jackson Hickel [8] presents a novel method for quantifying national contributions to climate change by evaluating cumulative CO2 emissions that exceed the planetary boundary of 350 ppm atmospheric CO2 concentration. The study's approach is grounded in the principle of equal per capita access to atmospheric commons and highlights the disproportionate responsibility of high-income nations for global emissions. This paper is pertinent to the analysis of VCMs from a planetary boundaries perspective, as it provides a mechanism for attributing responsibility for emissions that exceed global safe limits. Tol [9] examines the economic impacts of climate change, offering insights into the costs and benefits of various mitigation strategies, including carbon pricing. While Tol's work is primarily focused on the economic dimensions of climate change, it provides valuable context for understanding the broader economic implications of VCMs. His analysis highlights the importance of considering economic efficiency alongside environmental sustainability when designing carbon markets. By integrating Tol's economic perspective with the planetary boundaries framework, VCMs can be developed in ways that are both economically viable and environmentally sound.

Heck et al. [10] examine the potential unintended consequences of climate engineering techniques, particularly terrestrial carbon dioxide removal (tCDR), on planetary boundaries. Their study highlights the risk that interventions aimed at reducing atmospheric carbon may lead to the transgression of other boundaries, such as land system change. This is particularly relevant for VCMs, which often promote afforestation and other tCDR methods as carbon offset strategies. The findings suggest that VCMs must carefully consider the broader environmental impacts of their projects, ensuring that they do not contribute to the degradation of other critical Earth systems. This study underscores the importance of adopting a holistic approach to carbon markets, one that integrates multiple planetary boundaries into the evaluation and selection of carbon offset projects. Anderies et al. [11] explore the complex, non-linear dynamics of the global carbon cycle and its relationship with planetary boundaries. Their study emphasizes the existence of tipping points, beyond which minor changes in carbon dynamics could lead to significant and potentially irreversible shifts in the Earth system. It highlights the importance of maintaining carbon concentrations within safe limits to avoid crossing these tipping points. The study's findings support the need for VCMs to incorporate dynamic monitoring and adaptive management strategies that can respond to changing environmental conditions, thereby ensuring that carbon markets contribute to maintaining the Earth system within its safe operating space. Rockström et al. [1] introduced the planetary boundaries framework, which has become a cornerstone of environmental science and policy. The framework identifies nine critical Earth system processes [2] that must be maintained within specific limits to avoid catastrophic environmental change. Rockström et al.'s [1] study offers the theoretical basis for assessing whether carbon markets are contributing to or detracting from global environmental sustainability. The planetary boundaries framework serves as the guiding principle for evaluating the environmental integrity of VCMs and ensuring that they operate within the Earth's safe operating space.

Huang et al. [12] propose a methodology for downscaling planetary boundaries to the national level, using Taiwan as a case study. This approach allows for the assessment of environmental sustainability at a more localized scale, which is critical for the effective implementation of VCMs. By applying the planetary boundaries framework to specific regions or countries, VCMs can be designed to address local environmental challenges while contributing to global environmental sustainability goals. It provides a practical example of how the planetary boundaries framework can be adapted to different scales, offering insights into how VCMs could be tailored to meet the unique environmental needs of different regions.

This review consolidates the foundational frameworks and methodologies essential for understanding the role of voluntary carbon markets (VCMs) within the planetary boundaries context. The analysis by Engström et al. [7] serves as the cornerstone, demonstrating how carbon pricing can be integrated with planetary boundaries to mitigate multiple environmental pressures simultaneously. Complementary studies by Hickel [8], Tol [9], Heck et al. [10], and Anderies et al. [11] provide critical insights into the economic, ecological, and dynamic complexities of implementing VCMs in a way that is both environmentally and economically sustainable. These works collectively underscore the necessity of adopting a holistic, adaptive approach to carbon markets, ensuring that they contribute to global environmental sustainability without exacerbating other critical environmental challenges. The adaptability of the planetary boundaries framework developed by Rockström et al. [1], as demonstrated by Huang et al. [12], further emphasizes its applicability at various scales, making it a vital tool for tailoring VCMs to both global and regional environmental needs.

3. Methodology

To develop a comprehensive methodology for assessing how VCMs should be compensated within the planetary boundaries' framework, it is crucial to categorize the main types of VCM methods, describe each one in detail, and identify the specific planetary boundaries they most directly impact. The types of projects are going to be divided as shown in Figure 1, taking one project in each category as an example.

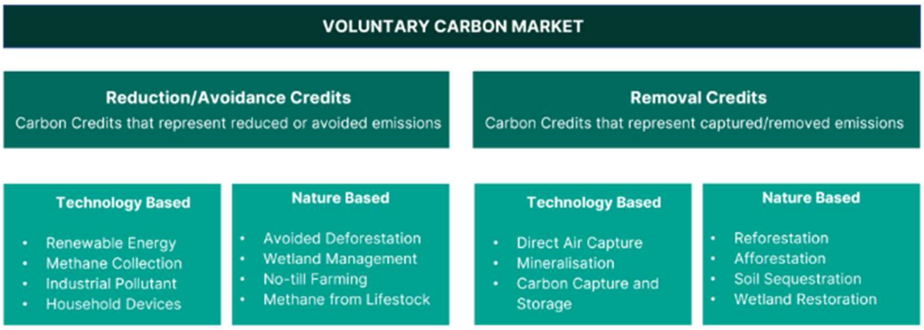

Figure 1 Types of Projects in the Voluntary Carbon Market [13]

Each type of project must be assessed as shown below, along with its relevance to specific planetary boundaries.

3.1. Renewable Energy Projects

Renewable energy projects involve the generation of energy from sources that are naturally replenished, such as wind, solar, hydroelectric, and biomass. These projects are a cornerstone of efforts to reduce greenhouse gas emissions by displacing fossil fuel-based energy generation. Renewable energy technologies vary widely in their environmental impacts, depending on the type of energy produced and the scale of the infrastructure [14]. The main boundaries affected are:

- Climate Change: Renewable energy projects, such as wind, solar, and hydropower, reduce reliance on fossil fuels and thus decrease greenhouse gas emissions.
- Biosphere Integrity: The development of renewable energy infrastructure can disrupt local ecosystems, especially if not effectively managed. For example, wind farms may impact bird and bat populations, while solar farms can affect ground-dwelling species.
- Land-System Change: Large-scale renewable energy projects often require significant land use, potentially leading to land conversion and landscape changes that affect local ecosystems and land-use patterns.
- Freshwater Use: Certain renewable energy projects, particularly hydropower, can significantly impact freshwater systems by altering water flow, affecting aquatic ecosystems, and potentially leading to conflicts over water resources.

3.2. Improved Forest Management (IFM)

Improved Forest Management (IFM) refers to a set of practices aimed at enhancing the carbon sequestration capacity of existing forests through better management techniques. These practices include extending rotation ages, reducing the impact of logging, avoiding deforestation, and promoting natural regeneration. IFM is focused on maintaining and increasing the carbon stock in forests while simultaneously ensuring the environmental sustainability of forest ecosystems [15]. The main boundaries affected are:

- Climate Change: IFM practices aim to increase carbon sequestration in existing forests through methods such as extended rotation ages, reduced impact logging, and avoiding deforestation.
- Biosphere Integrity: IFM can positively impact biodiversity by preserving existing forests and enhancing habitat quality. However, intensive management practices may also disrupt natural forest dynamics.
- Land-System Change: By maintaining or enhancing forest cover, IFM influences land-use patterns and can reduce pressures on land conversion for agriculture or urban development.

- Biogeochemical Flows: IFM affects nutrient cycles by altering forest management practices, which can influence soil composition and water quality.

3.3. Direct Air Capture (DAC)

Direct Air Capture (DAC) is a technology that captures CO2 directly from the ambient air using chemical processes. The captured CO2 can then be stored underground in geological formations or used in various industrial applications, such as carbonating beverages or synthetic fuels. DAC is seen as a complementary technology to natural carbon sequestration methods, offering the potential to reduce atmospheric CO2 levels, especially when emissions reductions alone are insufficient to meet climate targets [16]. The main boundaries affected are:

- Climate Change: DAC technology captures CO2 directly from the atmosphere and stores it underground or uses it in industrial processes, providing a direct method to reduce atmospheric CO2 levels.
- Energy Use and Indirect Impacts: While DAC primarily impacts the climate change boundary, the energy required to operate DAC systems can indirectly affect other boundaries. For instance, if the energy comes from fossil fuels, it could negate some of the climate benefits and impact other planetary boundaries, such as biosphere integrity (through air pollution) and land-system change (through energy infrastructure development).
- Freshwater Use: Some DAC systems require significant amounts of water, particularly if the captured CO2 is used in processes like enhanced oil recovery or mineral carbonation, impacting freshwater availability.

3.4. Afforestation/Reforestation (A/R)

Afforestation refers to planting trees on land that has not been forested for a long time, while reforestation involves replanting trees on land that was recently deforested or degraded. These methods are widely recognized for their ability to sequester carbon dioxide from the atmosphere through the natural process of photosynthesis, where trees absorb CO_2 and store it as biomass in the soil. Afforestation and reforestation are considered effective strategies for mitigating climate change by enhancing carbon sinks and restoring degraded ecosystems [17], [18]. The main boundaries affected are:

- Climate Change: A/R projects sequester carbon, directly reducing atmospheric CO_2 levels, which is critical for staying within the climate change boundary.
- Land-System Change: These projects involve significant changes in land use, converting land to forested areas, which can impact local ecosystems, agriculture, and natural habitats.
- Biosphere Integrity: The biodiversity impacts of A/R projects can vary widely. While they can enhance biodiversity by restoring natural habitats, they may also reduce it if monocultures or non-native species are planted.
- Biogeochemical Flows: A/R projects can alter nutrient cycles, particularly nitrogen and phosphorus flows, by changing the vegetation cover and soil composition.
- Freshwater Use: The establishment and maintenance of forests require water, and A/R projects can influence local and regional water cycles, affecting freshwater availability and quality.

3.5. Characteristics of the methodology

This methodology outlines a structured approach to assess the impact of voluntary carbon market (VCM) projects on each planetary boundary, employing a non-additionality framework. The non-additionality approach (based on Kate Raworth Doughnut Economics [19]) focuses on evaluating the environmental impacts of VCM projects without compensating the impact to one boundary with another, in other words, a VCM project should never worsen any of the planetary boundaries. Additionally, the actual state of the boundaries must be considered, prioritizing those that are being transgressed over those that are within the limits. These two characteristics, non-additionality and transgression analysis are the main new components of this VCM analysis, implementing them in the existing market will give a better understanding of the existing earth systems to companies and citizens and will focus on climate change in a more holistic view.

The non-additionality approach evaluates VCM projects based on their overall environmental impact, studying the impact on every boundary individually without compensating one for another. This approach helps to pre-empt new transgressions of different planetary boundaries, rather than compensate for damage that has already occurred. While it may seem that a reduction in carbon dioxide emissions is the main solution to climate change, in the future there may be another earth system that threatens human life, re-creating another compensating market focused on another planetary boundary. It is therefore more appropriate to approach this market with a holistic view as soon as possible, avoiding improving one planetary boundary at the expense of worsening another. Figure 2 shows how this method will influence different boundaries.

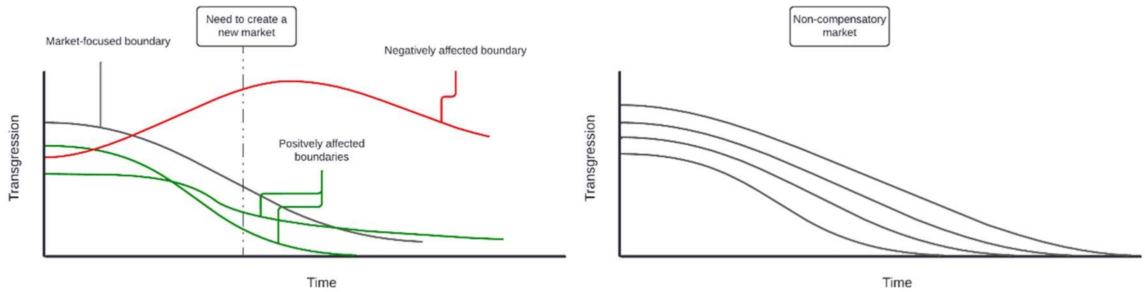

Figure 2 Left: Single boundary market effect on multiple planetary boundaries. Right: Holistic market effect on multiple planetary boundaries.

Analysing the current transgression of each limit allows for variable remuneration in terms of the improvement caused by each limit. A percentage method as used by the study of Engström [7] is proposed. Engström et al. analyse the percentual improvement in each boundary caused by an incremental increase in carbon tax (Figure 3), adapted to the VCM, each project should have an image as Figure 3 indicating how it will contribute to each boundary. This approach will allow a faster and more efficient recuperation of the set of all boundaries as shown in Figure 4.

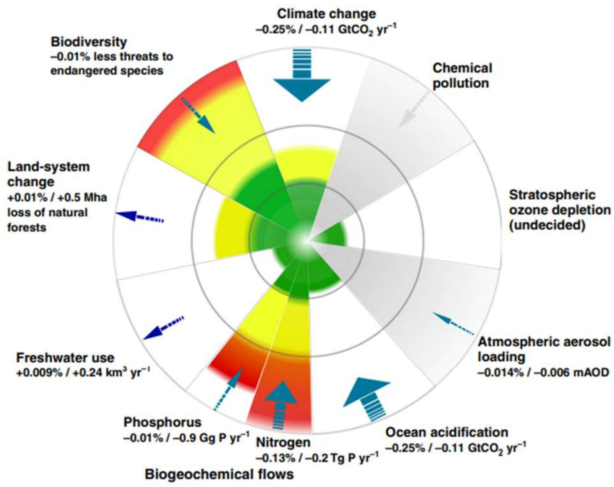

Figure 3 Changes in planetary pressures resulting from a one percentage point increase in the carbon tax [7].

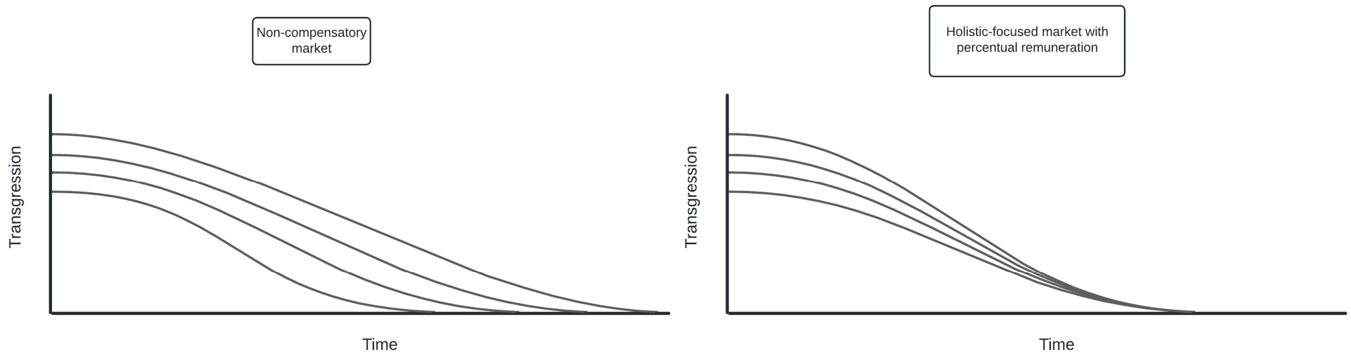

Figure 4 Left: Holistic market effect on multiple planetary boundaries. Right: Holistic market with percentual remuneration effect on multiple planetary boundaries.

This simple analysis shows how the actual VCM may be unsuitable for the complete list of planetary boundaries. In the study made by Engström et al. [7] they concluded that without proper bio-fuel restrictions, some boundaries might be negatively affected by an increase in carbon tax price. In this study, a quantitative analysis is not going to be done, but a guide to a better understanding of how projects affect the whole planet system is developed.

3.6. Steps for Boundary Impact Assessment

The process of analysis of each project, creating a variable for each boundary and combining them to create a score could turn out to be too complex. The current market is not considered ready for this assessment; therefore, a simpler guide is needed so companies and individuals can adapt the actual score based only on carbon dioxide reduction to what in this paper is going to be called the planetary index. This method must end with a number that correctly represents the impact of a certain project on the planetary boundaries, using non-additionality and transgression analysis. The following steps outline the general methodology to assess the impact of VCM projects on planetary boundaries:

1. Boundary Transgression Analysis

The analysis of the current state of each boundary is necessary to determine which one is more necessary to work on. It is not done by companies, it is done by scientists based on existing scientific literature, such as Steffen et al. (2015) [4]and Rockström et al. (2009) [1]. This step involves understanding how far each boundary has been transgressed and what the safe operating space is. It should be done periodically to show how changes in human behaviour and the implementation of these guidelines affect the state of the planet. This step also shows what boundaries should the projects focus on—the last study was made by Richardson et al. [2] in 2023 as shown in Figure 5.

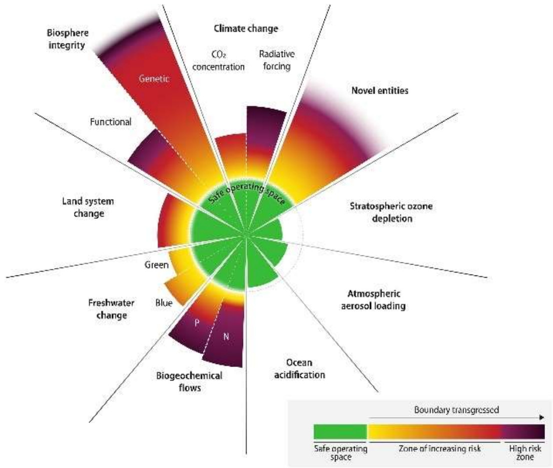

Figure 5 Current status of control variables for all nine planetary boundaries [2].

2. Project Impact Mapping

Once the boundaries are displayed, each individual must map out the potential impacts of VCM projects on each boundary. This includes direct impacts (e.g., carbon sequestration affecting the climate change boundary) and indirect impacts (e.g., land use changes affecting biosphere integrity and land-system change).

3. Impact Quantification

Quantify the impact of each project on the relevant planetary boundaries. This step involves using established indicators and models to measure how the project influences key variables within each boundary. For example, changes in land use might be quantified using satellite data, while impacts on nitrogen cycles could be measured through nutrient budgeting.

4. Integration of Boundary Transgression Levels

Integrate the degree of boundary transgression into the impact assessment. Projects should be evaluated more critically in areas where the planetary boundary is already heavily transgressed. For instance, a project in a region where biodiversity loss is significant should be scrutinized for its potential to either alleviate or worsen that boundary's state.

5. Cumulative Impact Consideration

Consider the cumulative impacts of multiple VCM projects within a region or on a global scale. Even if a single project has a minimal impact, its cumulative effect, when combined with other projects, could push a boundary further toward or beyond its threshold. This is important in projects that could worsen a specific boundary, but combined with another makes a synergy that improves the complete list of boundaries.

6. Holistic Environmental Review

Conduct a holistic review that considers how the impacts on one boundary might affect others. For instance, afforestation projects might improve carbon sequestration but could negatively impact water availability or biodiversity. The goal is to ensure that mitigating one boundary’s transgression does not inadvertently worsen another. This may be completed in step 3 and should now give a number that represents the holistic impact on the planet system, the planetary index associated with that specific project (or collection of projects). The following formula is proposed to derive the planetary index with the characteristics that have been developed:

$$\mathrm{PI\ (pi)} = \mathrm{abs}\left(\sum(\mathrm{t}_{\mathrm{e}_\mathrm{n}} \cdot b_{t_n})\right) \cdot sign(\min(t_e \cdot b_t)) \quad (1)$$

$$t_\mathrm{e}(\%) = \frac{\mathrm{CV_{bp}} - \mathrm{CV_{ap}}}{CV_{bp} - PB} \quad (2)$$

$$b_t(\%) = \min\left(\frac{CV_{bp} - PB}{PB}, 0\right) \quad (3)$$

$$b_{t_2}(\%) = \min\left(\frac{PB - CV_{bp}}{CV_{bp}}, 0\right) \quad (4)$$

Where *PI* is the planetary index which has been assigned a unit named pi (planetary index), t_e is the percentual transgression effect that the project has, and b_t is the percentual transgression of the boundary, CV_{bp} is the control variable value before the project is executed, CV_{ap} is the control variable value after the project is executed, and *PB* is the planetary boundary. Each planetary boundary will have one t_e associated to the project, and a b_t representing how transgressed it is in the time of execution of the project. Each project will have one *PI* associated. b_{t2} means the same as b_{t2} but it is used whenever a planetary boundary has a lower limit, while b_t is used when it has an upper limit.

Therefore, b_t represent how transgressed is the planetary boundary, in the case of climate change (atmospheric CO_2 concentration), b_t is $b_t = \min\left(\frac{417-3}{350}, 0\right) = 19.14\%$. If the boundary it is not transgressed, the value should be cero. If the project helps reduce the value to 416 ppm, it's t_e would be $t_e = \frac{417-4}{417-350} = 1.49\%$. If no other boundary is affected, the project's *PI* would be $PI = 1.49\% \cdot 19.14\% \cdot 1 = 2.85 \cdot 10^{-3} pi = 2.39\ mpi.$

It is shown that higher effects and more transgressed boundaries have more importance, while lower effects in boundaries that are less transgressed have lower importance. Any effect on planetary boundaries that are not transgressed will have no effect on the *PI*. As the absolute value of the outcome, it is multiplied by the sign of the lower effect, if only one boundary is worsened by the project, the whole planetary index will be negative. Therefore, the two main characteristics of this index are achieved, it gives more importance to projects that affect positively more transgressed boundaries, and it does not let to affect negatively any boundary conserving a positive *PI*.

7. Outcome Categorization:

Categorize the outcomes based on whether the project helps to bring the boundaries back within its safe operating space, maintains the current state without further transgression, or contributes to additional transgression. This categorization guides the decision-making process for project approval and compensation.

3.7. Application example

This framework should be applied across all types of VCM projects identified earlier, each project's specific impact on the planetary boundaries will be assessed using the general steps outlined, with particular attention to the unique challenges and opportunities associated with each project. By following this methodology, VCM projects can be thoroughly assessed for their environmental impacts across all planetary boundaries, ensuring that their implementation contributes positively to global environmental sustainability goals without exacerbating existing environmental crises. To illustrate the application of the methodology described above, let's consider an afforestation/reforestation (A/R) project. This example will demonstrate how the non-additionality approach and the assessment of impacts on planetary boundaries would be implemented in practice. The boundaries affected by this project are the ones described in the previous chapter. It is important to note that each project will affect different boundaries and that this is just an example.

Step 1: Boundary Transgression Analysis

This analysis will be made with the values derived from Richardson et al. (2023) [2] with the boundaries that are affected by the project using Equations 3 and 4.

- Climate Change: The climate change boundary is currently transgressed, in its two subdivisions: 417 ppm CO_2 with a boundary of 350 ppm and 2.91 W/m^2 with a boundary of 1.0 W/m^2. This means they are being transgressed by 19.14% and 191% respectively, so a positive effect on total anthropogenic radiative forcing at the top-of-atmosphere will have a greater impact in the *PI* of the project.
- Land-System Change: The land-system change boundary is also transgressed, with a global area of forested land of 60%, with a boundary of 75%. This means a transgression of 25% (b_{t2}).
- Biosphere Integrity: Biodiversity loss is severe, with species extinction rates far exceeding the natural background rate. This boundary is heavily transgressed, particularly in areas where deforestation and habitat loss are prevalent. With values of >100 E/MSY with a boundary of <10 E/MSY, and 30% HANPP with a boundary of <10%. It implies a transgression of 900% for genetic diversity and 200% for functional integrity.
- Biogeochemical Flows: Both nitrogen and phosphorus cycles are significantly disrupted, with excess nutrient runoff contributing to water pollution and ecosystem degradation. With values of 105% transgression for phosphorus and 206% for nitrogen.
- Freshwater Use: In some regions, freshwater use is near or beyond sustainable limits, with significant implications for ecosystem health and water availability. With values of 78% for blue water and 42% for green water.

Step 2: Project Impact Mapping

- Climate Change: The project is expected to sequester carbon by trees, which will absorb CO2 from the atmosphere and store it in biomass and soil.
- Land-System Change: The project will convert previously non-forested or degraded land into forest, altering the land-use pattern and potentially impacting local ecosystems.
- Biosphere Integrity: Depending on the species planted, the project could either enhance biodiversity (by planting native species and restoring natural habitats) or reduce it (by introducing monocultures or non-native species).
- Biogeochemical Flows: Changes in vegetation cover will influence nutrient cycling, particularly nitrogen and phosphorus, potentially leading to altered soil fertility and nutrient runoff.
- Freshwater Use: The project may require significant water resources, especially during the initial establishment phase, potentially affecting local water availability and altering hydrological cycles. However, in the long-term, it may improve water percolation and availability.

Step 3: Impact Quantification

This paper is not going to quantify the impacts of the A/R project on each planetary boundary. The result should give the expected reduction of every planetary boundary by the project. For example, if this specific reforestation captures CO_2, the result should give the quantity of CO_2 absorbed and the boundary transgression change in ppm, so it can be used as in Equation 2.

Step 4: Integration of Boundary Transgression Levels

Once every impact and transgression has been quantified, this step will show which impact will vary more on the final planetary index using Equation 2, and if changes in the project are needed to make it positive, or more profitable. It will also help to analyse how this project, when combined with other similar projects in the region, might contribute to overall changes in land cover, biodiversity, and hydrology. This analysis will help in understanding the broader regional impacts of afforestation and reforestation efforts.

Step 5: Cumulative Impact Consideration

If the project shows environmental deficiencies, it can be grouped with other projects in the area so they can co-benefit. For instance, if the reforestation requires worsening the freshwater boundary, a restoration of nearby water bodies could be done.

Step 6: Holistic Environmental Review

The final *PI* is calculated using Equation 1. Using all the tools described, any project should be capable of obtaining a positive *PI*, by adapting to the set of all the boundaries. Taking the value of *PI* calculated in Chapter 5.7, if reforestation has a negative effect on biodiversity by a quantitative calculation of 0.01 increment in the loss of species per year the calculation would be $t_{e_2} = \frac{100-100.01}{100-10} = -0.01\%$. Then, the *PI* would be $PI = abs(2.85 \cdot 10^{-3} + 900\% \cdot -0.01\%) \cdot -1 = -1.95 \cdot 10^{-3} pi = -1.95\, mpi$. This project could not enter the market. It would be obligated to adapt the reforestation with more biodiversity (Figure 6), recalculating another t_{e2}, this time reducing the loss of species by 0.05, with $PI = (2.85 \cdot 10^{-3} + 900\% \cdot 0.05\%) \cdot 1 = 7.35\, mpi$ (

Figure 6 Left: Single tree species reforestation. Right: Multiple species reforestation.

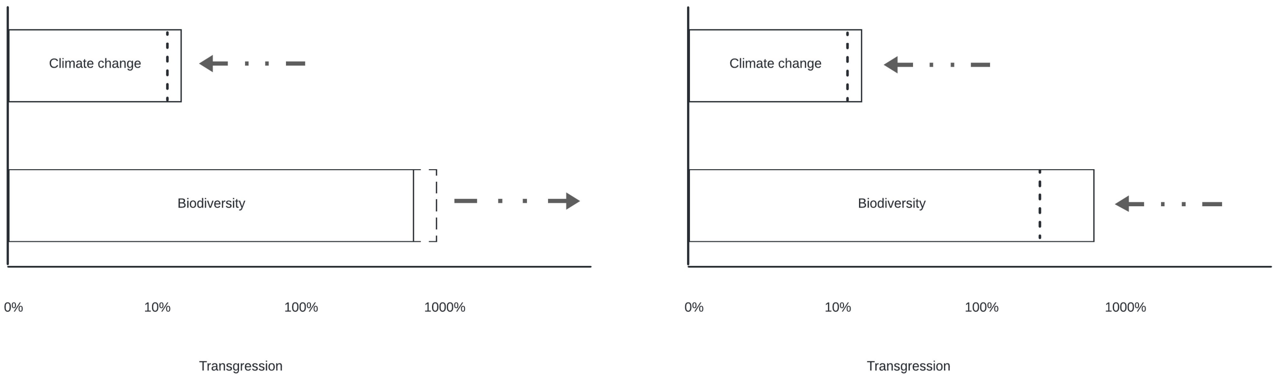

Figure 7 Left: planetary boundaries effect without non-compensatory measures. Right: planetary boundaries effect with non-compensatory measures considered.

Step 7: Outcome Categorization

- Positive: If the project contributes to bringing one or more boundaries back within their safe operating space, it will be categorized as positive.
- Neutral: If the project maintains the current state without further transgression, it will be categorized as neutral.
- Negative: If the project contributes to additional transgression of any boundary, it will be categorized as negative.

4. Results

This study represents a methodology for the evaluation of voluntary carbon markets (VCMs) through the lens of planetary boundaries, using a non-additionality approach. The application of this methodology to VCM projects. In the example derived from the A/R project, it is shown how a change in the currency of the market can lead to environmental improvements in the project. While with the current market, a complete reforestation with the same type of tree may lead to a higher CO_2 absorption per monetary spent ratio, the actualized analysis and the planetary index solutions for biodiversity makes the project more profitable (higher *PI* to monetary spent ratio) with more complete solutions, as shown in Figure 8.

This methodology and implementation strategy allows for better projects will be developed, and synergies will now be searched. Instead of creating single profitable projects, more complex and holistic projects will be looked for to increase profitability. Therefore, companies will have a better understanding of earth systems, downscaling it to their employees, creating a more responsible and educated population. While specific quantitative results have not been developed, this new vision together with the method described above helps to find a way to link the economy and the environment.

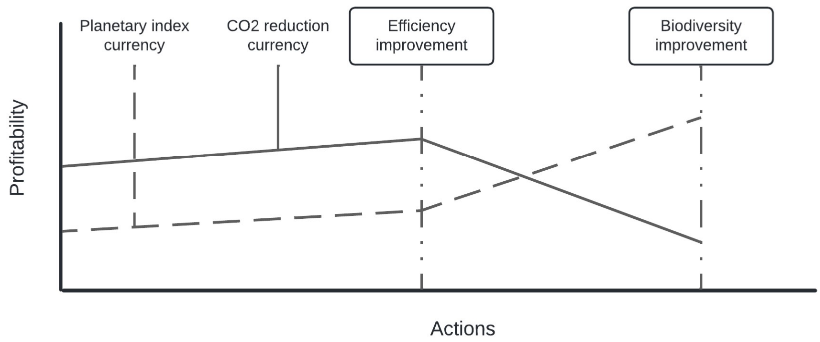

Figure 8 A/R project actions effect with different market currencies.

5. Conclusion

The findings from this study provide valuable insights into the interactions between voluntary carbon markets (VCMs) and planetary boundaries. By applying a non-additionality approach, the study highlights the necessity of evaluating VCM projects not just for their carbon sequestration potential but for their broader environmental impacts across multiple boundaries. This approach ensures that VCMs contribute holistically to global environmental sustainability goals without exacerbating existing environmental challenges. One of the key conclusions of this study is the recognition that while VCMs, can positively impact the climate change boundary, their overall effectiveness is constrained by the closed view of remunerating the effect on a single boundary. The study underscores the importance of integrating VCMs into a broader climate mitigation strategy that includes systemic policy measures, technological innovations, and lifestyle changes to achieve meaningful reductions in atmospheric CO2 levels.

Moreover, the study reveals that VCMs have significant potential to influence how future boundaries evolve, and how with a clear and complete perspective all planet processes and systems can be considered, ensuring a reduction in the transgression of all boundaries, and not just carbon dioxide. The method proposed in this paper should not be forced, as a slow implementation will gradually enhance projects to adapt to more complete solutions and educate the population on more holistic views.

In terms of future research, the study suggests that the non-additionality approach could be quantitatively expanded by developing specific indicators and models that measure the impacts of VCMs on each planetary boundary. It is also interesting to investigate short- and long-term effects on the boundaries, such as if watering more plants now could worsen the short-term boundary but improve it in the long term, and what limits should be proposed. In addition, a temporal more urgent market could be made only considering those boundaries that have transgressed the upper end of the zone increasing risk defined by Richardson et al. [2].

The evolution of this methodology could involve incorporating real-time monitoring data and adaptive management practices into VCM assessments. By using satellite data, IoT sensors, and other monitoring technologies, VCMs could dynamically respond to changes in the state of planetary boundaries, allowing for more flexible and responsive management strategies. This would enhance the ability of VCMs to contribute to long-term environmental sustainability while minimizing the risks of boundary transgressions.

In conclusion, this study provides a robust framework for assessing the impacts of VCMs on planetary boundaries, offering a path forward for more sustainable and holistic carbon market practices. By integrating non-additionality principles and focusing on the broader environmental context, VCMs can be better aligned with global environmental sustainability goals, contributing to the preservation of Earth's critical systems while supporting climate change mitigation efforts. Future developments in this field should focus on enhancing the quantitative tools available for boundary assessments, improving real-time monitoring capabilities, and fostering greater collaboration between stakeholders to ensure that VCMs deliver on their promise of a more sustainable future.

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